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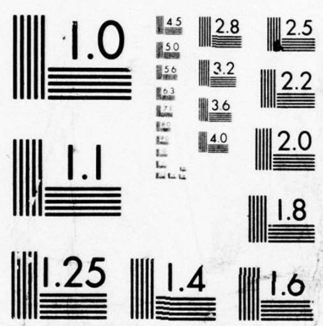

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FOREIGN TECHNOLOGY DIVISION

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FREQUENCY SINTHESIZERS

by

Vladimir Volarevic

FOREIGN TECHNOLOGY DIVISION

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FREQUENCY SINTHESIZERS

Vladimir Volarević, techn. major, graduated engineer

Synthesizers are complex systems for generating a large number of stable frequencies.

The reduction of the radio-transmitter frequency band-widths due to the ever increasing number of communication devices that cause a saturation of the available frequency bands, and the required high quality of transmission require highly stable radio frequency sources. Sources of high frequencies based on the principle of adding frequencies, ie., synthesis, enable the use of multiple channel devices with fast selection of the desired channel. Similar problems are encountered with the construction of measuring generators.

I. PROBLEMS OF CHOOSING FREQUENCIES IN MULTIPLE CHANNEL OSCILLATORS.

1. Multiple channel oscillators

The principle of operation of a multiple channel oscillator is shown in Scheme 1.

Scheme 1

A quartz oscillator - as the basic oscillator - generates reference frequencies. Reference frequencies are ordinarily between 1 and 10 MHz because these frequencies allow for quartz oscillatros of maximal precision.

The reference frequency is divided in the next step with integer N and in the next step is multiplied with integer R.

The desired frequency at the multiple channel oscillator output is R times the smallest desired frequency step f_o/N:

$$f_{izl.} = \frac{f_o}{N} \cdot R \qquad (1)$$

Individual synthesizers do not have a built-in basic oscillator; it is connected depending on the need and intent of ensuring the desired frequency

stability.

The reference signal (f_0) can be obtained in several ways of which the most interesting ones are the following:

a) Employing the LF of the basic oscillator and multiplying the signal from the oscillator by transfiguration or respectively by selecting the desired signal with filters.

b) Using the HF of the basic oscillator along with frequency dividers.

The advantage of the second method of obtaining the reference signal is seen in the high stability of the frequencies generated by the crystals between 1 and 10 MHz and in easier filtering of the undesired frequencies compared to the method using multipliers.

The harmonics of the reference frequencies (f_0) are generated by leading a sinusoid signal through a quadrupole with an extremely nonlinear transmission characteristic (transistor or switched diode) or are generated in a nonlinear amplifier with a positive feedback.

2. Frequency synthesis and analysis.

If we decide, for example, on frequency 5683 MHz we can produce it as the sum of the fifth 1-MHz harmonic, the sixth 100-kHz harmonic, the eighth 10-kHz harmonic, and the third 1-kHz harmonic or else as the 5683rd 1-kHz harmonic.

The basic methods are therefore multiplication and summation of harmonics. The second method has a smaller number of reference frequencies and sums.

Therefore, there are two basic principles for generating a signal:

a) the principle of frequency synthesis

b) the principle of frequency analysis.

The main problem with both methods is in filtering the undesired components and in the purity of the desired harmonic.

The principle of frequency synthesis converts the output frequency by alternatingly combining or subtracting harmonics (subharmonics)from one or more quartz oscillators; and by selecting desired products, a large number of output frequencies is generated.

There are two methods that characterize the formation of individual frequencies: the passive method and the method of frequency transposition.

The passive method uses addition and subtraction to form a frequency decade with 9 equal frequency intervals and with divisor 1/10.

In the frequency transposition method the desired harmonic of the reference frequency is transformed by an auxilliary oscillator into a constant frequency situation while an additional filter removes undesired harmonics. The same auxilliary oscillator brings desired harmonics in the original position (Wadley method).

Frequency analysis compares the frequency signal from the relatively unstable oscillator with the harmonic of the etalon frequency signal (f_o) in a phase or frequency discriminator or in a combination of the two. The result of the comparison is a regulated voltage that the oscillator through a reactance tube or varactor adjusts to an exact or desired frequency.

The basic advantage of this method lies in the fact that it does not contain variable elements during the process of formation of the output signal, thus it is very applicable in practice.

This method can be divided into

a) synthesizers with a source of etalon frequency

b) synthesizers without a source of etalon frequency.

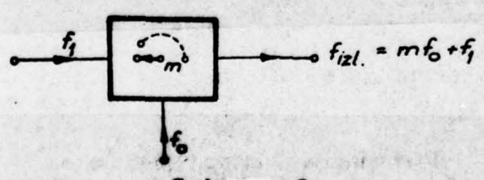
Synthesizers with an etalon frequency source use two methods:

a) method of impulse oscillator control, which compares frequency and phase or even frequency and phase of a freely variable oscillator and the etalon frequency source;

b) method of impulse frequency oscillator control with a variable divider, employing a frequency divider and comparison of phases.

3. Decade layout.

The selection of individual harmonics and their summation is performed using a decade (10 positions).



Scheme 2

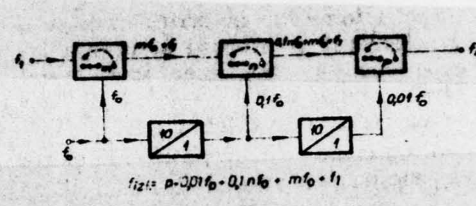
In Scheme 2 the decade output signal has a frequency

$$f_{izl.} = m \cdot f_o + f_1 \qquad (2)$$

where m can be any of 10 positions.

Digital dividers have decades with many more steps. For example, to each decade corresponds a series of 10 frequencies with the necessary step: 10 frequencies with 1-MHz step, 10 frequenices with 100-kHz step, etc.

Scheme 3 shows a series of three decades.



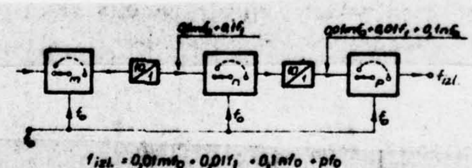
Scheme 3

In Scheme 3, the frequency of the signal exiting the three decades in a series is:

$$f_{izl.} = 0{,}01\,pf_0 + 0{,}1\,nf_0 + mf_0 + f_1 \quad (3)$$

where p, n, and m are integers.

Such series of decades have different output frequencies. In practice it is essential that decades do not differ in their construction and their output frequency. Such a system is depicted in Scheme 4, where fixed 10-dividers are positioned between the decades.



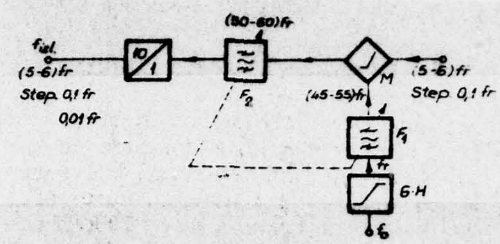
Scheme 4

The frequency of the output signal of the series of (equal) decades in Scheme 4 is

$$f_{izl.} = 0{,}01\,mf_0 + 0{,}01\,f_1 + 0{,}1\,nf_0 + pf_0 \quad (4)$$

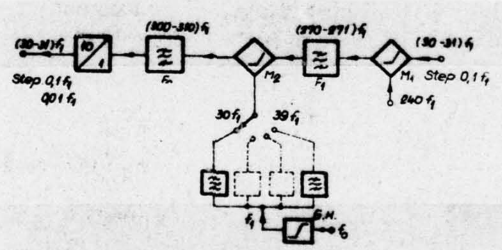
In this system the dividers reduce spurious components, which is considered advantageous.

Schomandl's principle of forming the so-called passive decade with band filters is depicted in Scheme 5.



Scheme 5

Band filter F_1 allows the passage of the frequency band $(45-55)f_r$ of the signal from the generator of harmonics G.H. This signal comes into the mixer M. The sum of this signal and signal $(5-6)f_r$ (with the possible change by $0.1\ f_r$) comes through the second band filter F_2. After division with 10 in the divider the output signal $(5-6)\ f_r$ is obtained with the possible steps of $0.1\ f_r$ and $0.01\ f_r$. The Hewlett-Packard system of passive decade, with fixed filters and frequency transposition in a series, is shown in Scheme 6.



Scheme 6

4. <u>Requirements for multiple channel oscillators.</u>

<u>A. Output signal purity</u>. The purity of the output signal is one of the basic requirements in the construction of multiple channel oscillators. In practice this can be accomplished with corresponding screening, decoupling. This helps in leaving out spurious signals (noise, intermodulation products) at the output.

Spurious components are mainly products of the mixing of frequencies in the mixing steps as well as undesired coupling. By international rules the radiating power of secondary components of the transmitter must be suppressed relative to the basic signal by 60 dB (even more for more powerful transmitters).

This suppression is accomplished with filters and with protection of sensitive elements. The oscillator output noise conditioned by the low voltage of the signal during the amplification and the mixing of signals must be suppressed by about 90 dB relative to the level of the basic signal.

The linearity of the signal delivery is assessed with a two tone check which brings to the input two close frequencies of the same level. Due to the non-linearity of the route there appear various combinatory components. These have to be weakened by about 50 dB relative to the basic signal.

B. Frequency stability. The stability of the frequency of the output signal must be high, ie., the generation of the signal must occur in some etalon frequency. Since the frequency stability depends on many factors a satisfactory stability is considered under the worst circumstances ($\pm$ 0.5 % for an oscillator with a reactance (varicap) and subjected to a temperature of 100^{o} and a $\pm$ 10% change in supply voltage).

C. Electronic tuning. Electronic tuning is a very important factor in the construction of multiple channel oscillators for the following reasons.

a) There are no mechanical connections that would cause wear of sliding parts, nor is their adjustment necessary;

b) simple control of the system is possible internally and from a distance;

c) there are no motors or servoloops;

d) the regulation of the tuning systems in the case of electronic tuning based on the decade principle represents no problem;

e) with solid state design the existence of microphonics is totally absent. This is a very important problem as it helps avert additional phase modulations of the oscillator signals.

f) The whole system (of the synthesizer) is constructively simple with separately screened boxes which adds to low spurious output.

5. Frequency multiplication - ways of separating desired frequencies.

A signal with high frequency stability if led to the generator of harmonics where it is formulated and enriched with higher harmonics.

For separation of the desired frequencies (harmonics, bands) one uses: passive filters, Wadley principle, an impulse-governed oscillator (IGO) loop, or a digital circuit.

A. Ways of separating desired frequencies with passive filters.

In view of the high damping of undesired components (>80 dB), filters with concentrated parameters have an advantage.

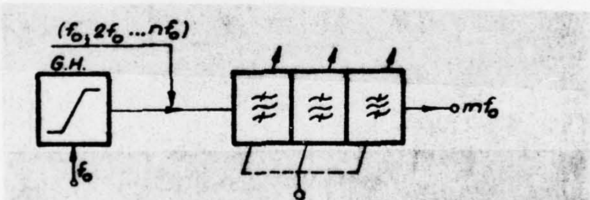
Passive filters can be realized as: piezo-ceramic, quartz, or composed of LC components.

The stated damping of undesired components with quartz filters can be accomplished on up to 200 harmonics, with piezo-ceramic to 50 harmonics, and with LC filters up to 20 harmonics of the desired signal.

Quartz and piezo-ceramic filters are used less often due to their specific construction and limited range.

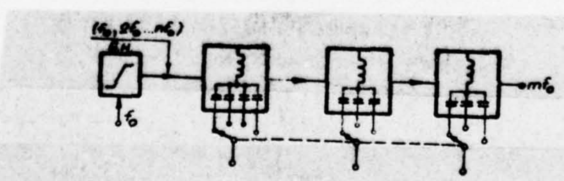
The means of filter commutation can be divided into

a) Non-switched tuning filters, continuously tuned on the desired harmonic, which belong to the oldest method (scheme 7).



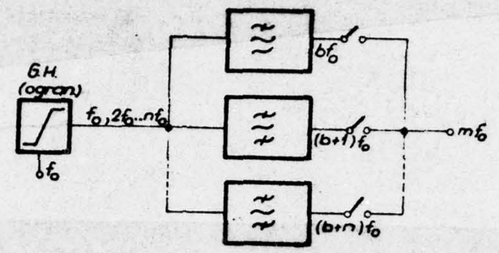
Scheme 7

b) Switched filters. Sections of the filter for separating desired harmonics are connected with a disc to a central switch (Scheme 8).



Scheme 8

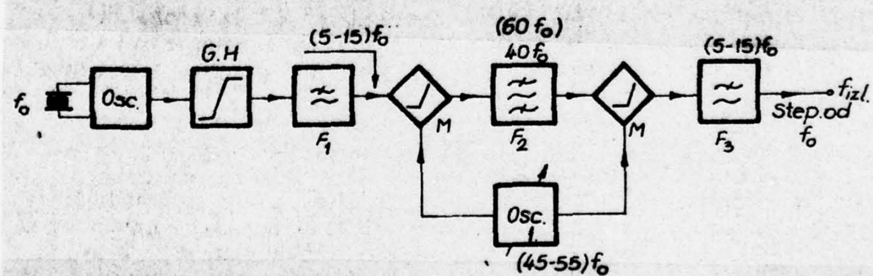
c) Filters for fixed selection of desired harmonics. This method of selection is often used in measuring generators for the selection of the desired component as the weight and volume of such devices is often not limited. Here one often utilizes crystal filters. The diagram for such a method of selection of the desired harmonics is shown in Scheme 9.



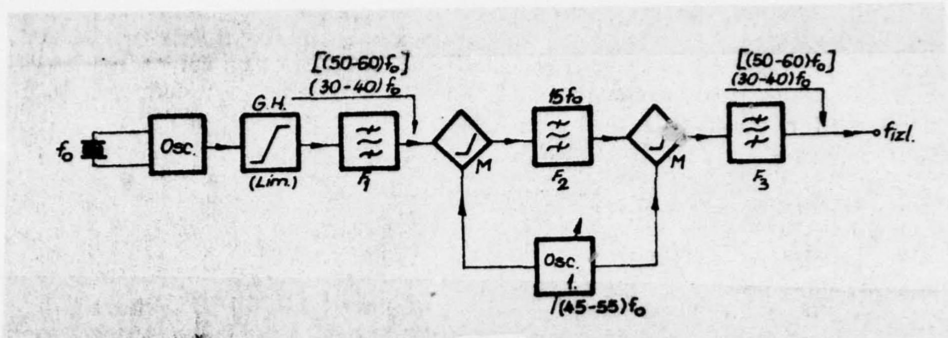
Scheme 9

The corresponding signal is connected electronically to the output. Because of the difficulties with the electronic tuning of multiple-step filters fixed filters are most often used in radio systems.

<u>B. Wadley method for separating the desired frequency</u>. The diagram for separating (multiplying) the desired frequency (spectrum) is shown in Schemes 10 and 11. The Wadley method with a high intermediate frequency is shown in Scheme 10 and with a low intermediate frequency in Scheme 11.



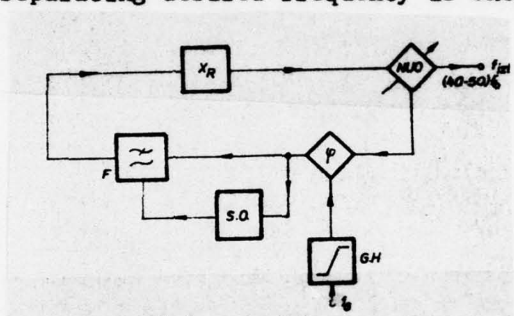
Scheme 10



Scheme 11

C. Method for separating the desired frequency with impulse-governed oscillator loops.

An IGO loop for separating desired frequency is shown in Scheme 12.



Scheme 12

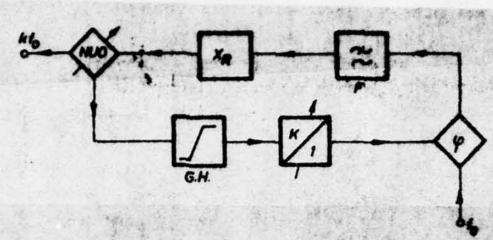
Signal frequencies and harmonics of the reference frequency (f_o) are compared in the phase discriminator φ. Depending on the phase difference between these two signals a control voltage appears as the output of the phase discriminator. It acts through the low-pass filter F on the reactance element X_R (varicap) of the voltage governed oscillator (VGO). The VGO is coarsely tuned electronically, whereas the fine tuning is accomplished with the reactance circuit X_R. If the VGO is coarsely tuned on the desired harmonic, the loop automatically brings it to the exact frequency.

The coarse tuning of the VGO to the desired harmonic must be accurate to $\pm$ 0.5 f_o. The stability of the electronic tuning of the LC oscillator with changes in temperature, voltage, and aging must be within $\pm$ 0.5% for the maximal oscillator frequency of 100 f_o. Such a loop ensures (40-50) f_o in steps if the output reference oscillator signal is f_o.

To ensure an uninterrupted performance of the loop over the entire frequency span, a new loop with a synchronizing oscillator is added to the circuit.

D. Method of separating the desired frequency with digital loops.

The digital loop that is used for multiplications of the desired signal in digital synthesizers, is shown in Scheme 13.



Scheme 13

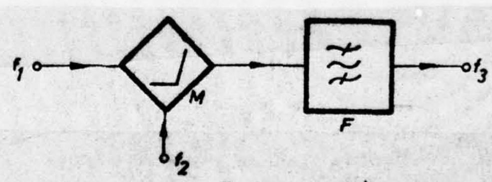
The loop contains a variable divisor K, a generator of harmonics G.H., a low-pass filter F, and a reactance element X_R. The phase discriminator compares the harmonics signals and the reference signal (f_o).

For fine gradation of the output signal, eg., in 100 Hz, which is needed here, K must be 300000 for f_o = 100 Hz and f_{VGO}= 30 MHz.

6. Frequency addition

When two frequencies f_1 and f_2 are brought to the mixing step M, a frequency spectrum $|mf_1 \pm nf_2|$ is generated (where m and n are integers).

The desired frequency or band of frequencies is separated with a band filter F (Scheme 14).



Scheme 14

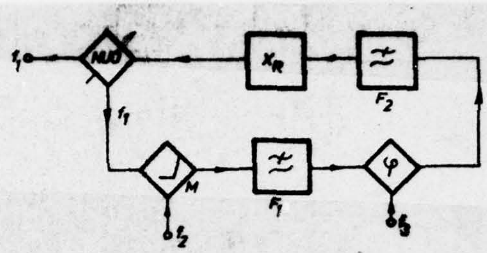
A signal with the desired frequency can be generated also in an addition loop (Scheme 15).

Signals f_1 and f_2 with a sinusoidal character are brought to the mixer M.

Frequencies f_2 and f_3 meet the condition:

$$f_2 > f_3 \text{ i } \Delta f_2 > \Delta f_3$$

If f_2 is subtracted from f_1 then in the moment of synchronization f_1 is equivalent to $f_2 + f_3$.

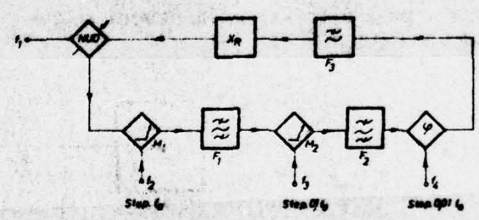


Scheme 15

F_1 is a low-pass filter that passes signal $f_1 - f_2$. In this case, therefore, one subtracts two high frequencies, but the result is a frequency lower than f_1 or f_2. The damping of undesired frequencies is much simpler with low-pass filter F_1.

For example, if $f_2/f_1 > 83$, the first undesired products are of 9th order, whereas for ratio $f_2/f_1 > 0.87$, the first undesired product is of 11th order. High requirement filters are not needed for such weak components.

Adding circuit for three frequencies is shown in Scheme 16.



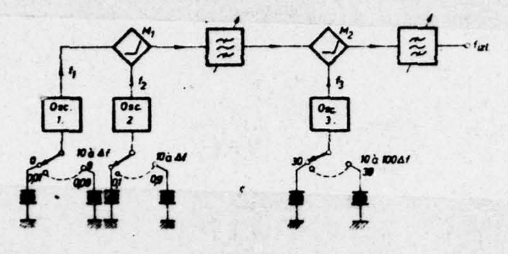
Scheme 16

II. DIRECT SYNTHESIS BY MIXING A LARGER NUMBER OF INDIVIDUAL FREQUENCIES.

By this method individual signals can be generated in multiple-crystal oscillators or in a basic oscillator with one crystal.

1. Generation of individual frequencies in oscillators with multiple crystals.

The diagram for this method is shown in Scheme 17.



Scheme 17

The following combination frequencies can appear as the output of the first mixer:

$$f_1+f_2;\ f_1-f_2;\ f_1\pm 2f_2, \ldots, |mf_1\pm nf_2| \quad (5)$$

The interval between neighboring frequencies is Δf. In the last step of the first crystal decade the difference between adjacent frequencies is $10\ \Delta f$, the output of the second $10 \times 10\ \Delta f$, whereas the output of the third is $10 \times 100\ \Delta f$.

The following frequencies appear as the output of individual oscillators:

$$f_1=f_1'+n_1\,\Delta f;\ f_2=f_2'+n_2\cdot 10\,\Delta f;$$
$$f_3=f_3'+n_3\cdot 100\,\Delta f$$
$$n_1=0,\ldots,9;\ n_2=0,\ldots,9;$$
$$n_3=0,\ldots,9 \quad (6)$$

The output signal frequency of the synthesizer is given by

$$f_{izl}=f_1+f_2+f_3=f_1'+f_2'+f_3'+$$
$$+\Delta f\,(n_1+10\,n_2+100\,n_3) \quad (7)$$

If, for example, $f_1' = 5$ MHz; $f_2' = 7$ MHz; $f_3' = 18$ MHz with a difference in adjacent frequencies of $\Delta f = 10$ kHz, then in the first step, after three selection sections (30 crystals, 1000 channels), the lowest output frequency is $f_{out\,1} = 5 + 7 + 18 + 0.01\ (0) = 30$ MHz,

whereas the frequency of the thousandth channel in the last selection step is

$f_{out\,1000} = 39.99$ MHz.

The relative simplicity of the system is considered to be its advantage.

The shortcomings of the system are considered to be:

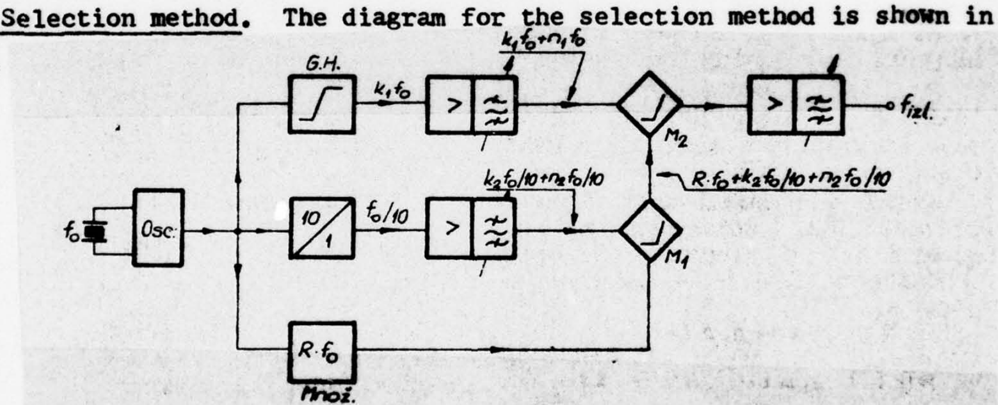
a) Mistakes of individual oscillators are cumulative. This flaw can be diminished if the output frequency is chosen to be a combination of sums and subtractions of previous signals.

b) The spectrum of the signal is not pure. In addition to the pure output frequency the synthesizer generates considerable combination frequencies between harmonics or even between harmonics and fundamentals.

2. Generation of individual frequencies in oscillators with a single crystal.

This method can be divided into the selection and the Wadley method of frequency transposition.

A. Selection method. The diagram for the selection method is shown in Scheme 18.



Scheme 18

The clipper (G.H.), by limiting produces many harmonics from f_0 (f_0, $2f_0$, $3f_0$,..., $100f_0$). As is known, Fourier analysis can separate a rectangular wave into a sum of many sinusoidal components.

The values of n_1 and n_2 are integers from 0 to 9, whereas k_1, k_2, and R are whole numbers.

The synthesizer output signal frequency is

$$f_{izl} = f_0\left(k_1 + R + n_1 + \frac{k_2 + n_2}{10}\right) \qquad (8)$$

where $n_1 = n_2 = 0,\ldots,9$.

If, for example, we choose f_o = 1 MHz and by selective separation (and amplification) k_1 = 17 and k_2 = 10 harmonic multiplied by R = 7, then after the first selection step the output signal is

$$f_{izl \cdot 100} = 1\left(17 + 7 + 0 + \frac{10+0}{10}\right) = 25\ \mathrm{MH_z}$$

and after the last step

$$f_{izl \cdot 100} = 1\left(17 + 7 + 9 + \frac{10+9}{10}\right) = 34{,}9\ \mathrm{MH_z}$$

Therefore, 100 different frequencies (channels) are generated in the frequency band from 25 to 34.9 MHz.

The disadvantages of this system are:

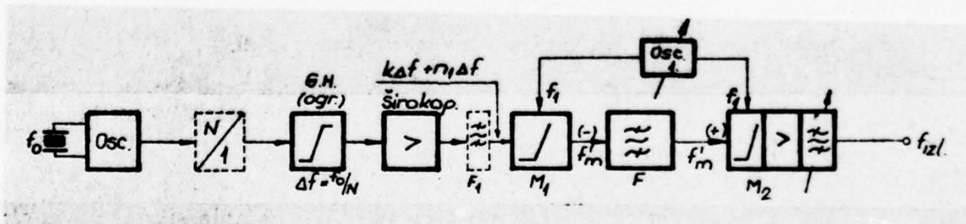
a) Difficulties in producing quality selective amplifiers;

b) need for a large number of high quality oscillation circuits (filters).

The advantage of this system is the signal generation from one crystal unit.

<u>B. Wadley method of frequency transposition.</u>

The diagram for generating individual frequencies by this method is shown in Scheme 19.



Scheme 19

The wide-band amplifier should produce the frequency or spectrum

$$k \cdot \Delta f + n_1 \cdot \Delta f \qquad (9)$$

which is in practice separated by the selecting filter F_1.

The frequency of OSC 1 in the regulating loop is

$$f_1 = k \Delta f + n_1 \Delta f - (f_m \pm d_f) \qquad (10)$$

where $n_1 = 0, \ldots, 9$, and f_m = central frequency of the band filter F.

The first mixer, which uses the frequency difference (-), produces f_m'. Using d_f, OSC 1 is tuned to the approximate value of one spectral component that is expected as the output.

The difference between the oncoming spectral components and the spectral components of OSC 1 passes through filter F into the first mixer (M_1):

$$\begin{aligned} f_m' &= (k \Delta f + n_1 \Delta f) - f_1 = \\ &= (k \Delta f + n_1 \Delta f - [k \Delta f + n_1 \Delta f - \\ &\quad - (f_m \pm d_f)] = f_m \pm d_f \qquad (11) \end{aligned}$$

Signals f_m' and f_1 arrive at the second mixer M_2 which uses the sum of the signals.

Such selectively separated and amplified signal is the synthesizer output:

$$\begin{aligned} f_{izl.} &= f_1 + f_m' = \\ &= [k \Delta f + n_1 \Delta f - (f_m \pm df)] + \\ &\quad + (f_m \pm df) = k \Delta f + n_1 \Delta f \qquad (12) \end{aligned}$$

The frequency of the variable oscillator does not appear in the formation of the output frequency due to the mixing that is repeated twice with the same frequency of the variable oscillator.

Thus, using the frequency of the variable oscillator the desired harmonic is separated from the rest of the harmonics spectrum.

The method of frequency transposition (Wadley method) is useful for cheaply obtaining a large number of highly stable frequencies from a single source of reference frequency, using a relatively unstable variable oscillator. The following relationships obtain in this method:

$$\text{a)}\ df < \Delta f_m$$

$$\text{a)}\ df < \Delta f_m < \frac{\Delta f}{2} \qquad (13)$$

If for example one takes Δf = 100 kHz, then the filter passing band must be $\Delta f_m < \Delta f/2$, or less than 50 kHz.

Let f_m = 0.5 MHz be the central frequency of the filter F. If the desired output spectrum is

$$f_{out} = 2 \rightarrow 2.9 \text{ MHz},$$

then the OSC.1 frequency must be

$$f_1 = 2 - 0.5 = 1.5 \text{ MHz}$$

$$f_{10} = 2.9 - 0.5 = 2.4 \text{ MHz}.$$

Depending on the addition step, in this case the output signal would be

$$f_{out}1 = 1.5 + 0.5 = 2 \text{ MHz}$$

$$f_{out}10 = 2.4 + 0.5 = 2.9 \text{ MHz}.$$

This method makes the most critical part of the system, filter F, frequency independent or tuned to the central frequency (f_m). This is a great advantage of the method.

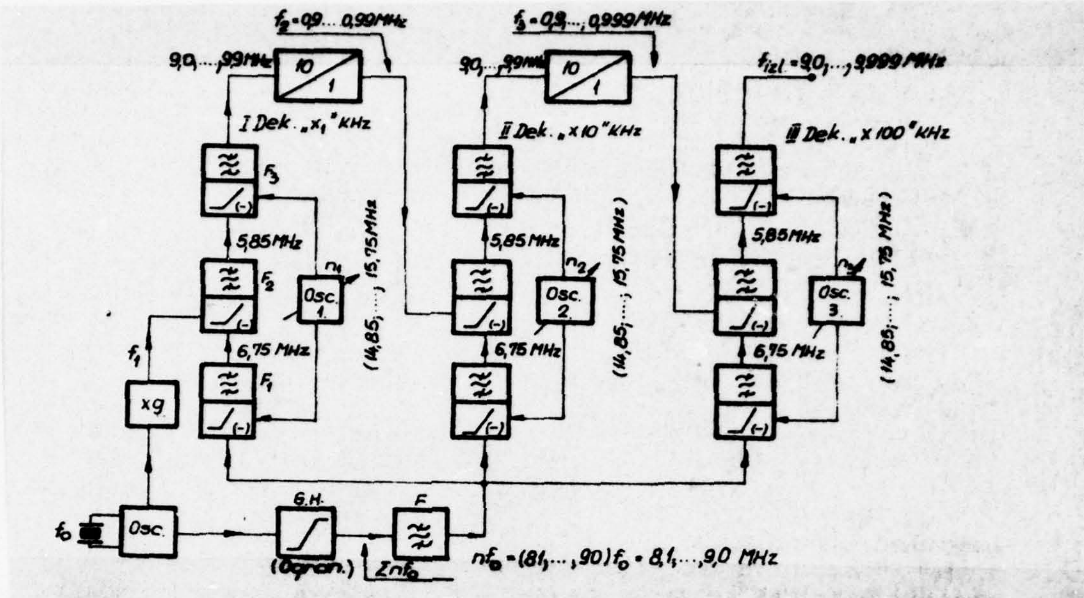
3. Construction of a multiple-channel oscillator based on the principle of frequency transposition.

Scheme 20 depicts a multiple-channel oscillator with frequency transposition (Wadley method).

The reference frequency f_o is 100 kHz. By modifying this signal (by limiting - generator of harmonics) Σnf_o is obtained. It is led into the band filter, which separates the spectrum 8,1,...,9,0 MHz, then into the decade mixers.

The variable oscillators (1,2,3) can be tuned to frequencies from 14.85 to 15.75 MHz in 9 100-kHz steps depending on n_1, n_2, and n_3.

By mixing the lowest frequencies of the variable oscillators with the lowest frequencies of the generated harmonics, the first intermediate frequency is obtained: $14.85 - 8.1 = 6.75$ MHz (14)



Scheme 20

All of the other 8.1 - 9.0-MHz components of the spectrum together with the other 14.85 - 15.75-MHz components of the variable oscillator form other intermediate frequencies that are damped by filter F_1, which passes only the signal of frequency 6.57 MHz. Filter F_2 in the first decade passes the difference between frequencies $f_1 = 9f_o$ and 6.75 MHz, which represents the second intermediate frequency:

$$6.75 - 0.9 = 5.85 \text{ MHz} \qquad (15)$$

The first-step selection on the variable oscillator 1 produces a filter F_3 output signal of

$$14.85 - 5.85 = 9.00 \text{ MHz} \qquad (16)$$

The last-step selection on the oscillator 1 produces a filter F_3 output signal of 9.9 MHz.

The 9.0 to 9.9-MHz signal spectrum is led to the frequency divider (by 10). The frequency changes in the first decade are carried out such that the same frequency relationships are obtained as in the other decades.

The frequency of the first decade is given by the formula

$$
\begin{aligned}
f_{izl.\ I\ DEK.} &= n_1 f_0 + 9f_0 = \\
&= [(81, \ldots, 90) + 9]\, f_0 = \\
&= 9{,}0, \ldots, 9{,}9 \text{ MHz} \qquad (17)
\end{aligned}
$$

where n_1 depends on the step in the region 81,..., 90. Due to the last mixing based on the difference principle, the frequency of the variable oscillator is lost and the precision of the first decade output frequency is the same as that of the signal f_o.

The 100-kHz intervals in the first decade are reduced by the divider to 10 kHz.

The same relationships hold for the other decades and can be derived similarly.

After the division in the first decade the signal frequency is determined by the formula

$$f_2 = \frac{n_1 f_o + f_1}{10} \qquad (18)$$

whereas after division in the second decade, the signal f_3 is

$$f_3 = \frac{n_2 f_o + f_2}{10} \qquad (19)$$

The frequency of the synthesizer output signal is given by the equation

$$f_{izl.} = n_3 f_o + \frac{n_2 f_o}{10} + \frac{n_1 f_o}{100} + \frac{f_1}{100} \qquad (20)$$

or

$$
\begin{aligned}
f_{izl.} &= (8{,}1, \ldots, 9{,}0) \text{ MHz} + \\
&+ \frac{(8{,}1 \ldots 9{,}0) \text{ MHz}}{10} + \frac{(8{,}1, \ldots, 9{,}0) \text{ MHz}}{100} + \\
&+ \frac{0{,}9 \text{ MHz}}{100} = 9{,}00, \ldots 9{,}999 \text{ MHz}
\end{aligned}
$$

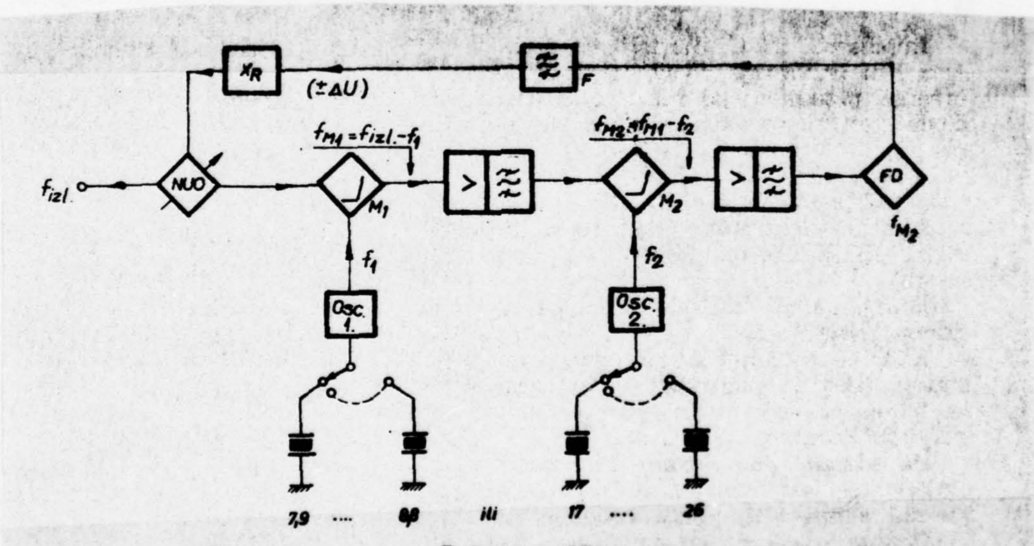
That means that by using one reference oscillator and three decades we generated 1000 frequencies (channels) in $f_{o/100}$(1 kHz) intervals, whereas the relative accuracy of the output signal is the same as the accuracy of the etalon oscillator frequency.

III. ANALYTICAL METHOD OF FREQUENCY SYNTHESIS WITH A REGULATION LOOP.

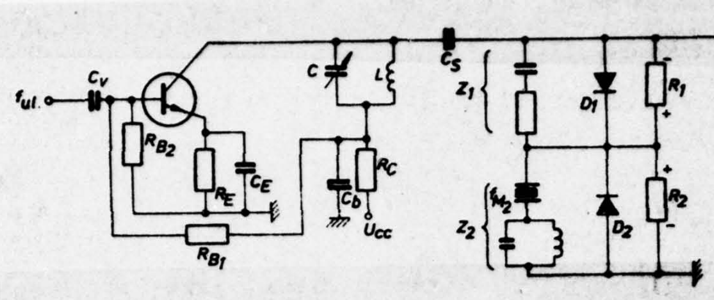
The realization of this method of generating a large number of stable frequencies comprises of the use of a frequency discriminator and a phase discriminator (comparator) or their simultaneous use. In what follows, all the processes will be therefore treated from a theoretical view of individual links in the system.

1. Analytical method of frequency synthesis with a regulation loop employing a frequency discriminator.

The diagram for the analytical method of frequency synthesis with a regulation loop employing a frequency discriminator is shown in Scheme 21. The central frequency of the frequency discriminator (FD, Scheme 22) is f_{M2}.

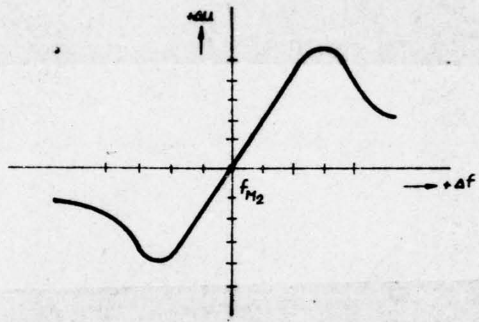


Scheme 21



Scheme 22

The dependence of the output voltage $\pm\Delta U$ on the scatter $\pm\Delta f$ for a given frequency discriminator factor is shown in Scheme 23.



S cheme 23

If the frequency discriminator input frequency f_{in} is equal to the central frequency f_{M2}, then impedances Z_1 and Z_2 are equal and the voltage drops on R_1 and R_2 are equal in the absolute value but opposite in direction, and the output voltage is 0.

If the input frequency is greater than f_{M2} by $+\Delta f$ due to $|Z_2| > |Z_1|$ then the discriminator output signal appears as an impulse $+\Delta U$ which is led through the band filter F into the voltage regulated oscillator (VGO).

In the case of $f_{in} < f_{M2}$, the FD output impulse is oppositely directed $-\Delta U$ which is again led through F to regulate the VGO.

The VGO is regulated with the impulse $\pm\Delta U$ by changing the inverse pre-voltage polarization of the varicap diode which is connected in parallel to

the circuit of the oscillator.

The VGO can be regulated also by regulating a reactance electron tube which is connected for this purpose in parallel to the oscillator circuit.

The VGO is set to a desired frequency such that the error of setting is not greater than the linear part of the frequency discriminator curve.

Using this method of frequency synthesis we managed to get 100 functional frequencies from 20 crystal units. The advantage of the system is in the purity of the output frequency.

As the frequency precision and stability of the frequency discriminator are limited, the error in precision and stability of the frequency oscillator is increased. Together this represents the disadvantage of the system.

Scheme 21 equates

$$\begin{aligned} f_1 &= f_1' + n_1 \Delta f \\ f_2 &= f_2' + n_2 10 \Delta f \end{aligned} \qquad (21)$$

or

$$\begin{aligned} f_{M1} &= f_{izl.} - f_1 = f_{izl.} - [f_1' + n_1 \Delta f] \\ f_{M2} &= f_{M1} - f_2 = f_{izl.} - \\ &- [f_1' + f_2' + n_1 \Delta f + n_2 10 \Delta f] \end{aligned} \qquad (22)$$

The frequency of the output signal is

$$f_{izl.} = f_{M2} + f_1' + f_2' + \Delta f (n_1 + 10 n_2) \qquad (23)$$

if $n_1 = 0,\ldots,9$; $n_2 = 0,\ldots 9$.

If in the construction of the synthesizer we decide on values

$$\begin{aligned} f_1' &= 17 \text{ MHz} \\ f_2' &= 7{,}9 \text{ MHz} \\ f_{M2} &= 0{,}1 \text{ MHz} \\ \Delta f &= 0{,}1 \text{ MHz} \end{aligned}$$

then the synthesizer would generate on the first channel a signal of frequency

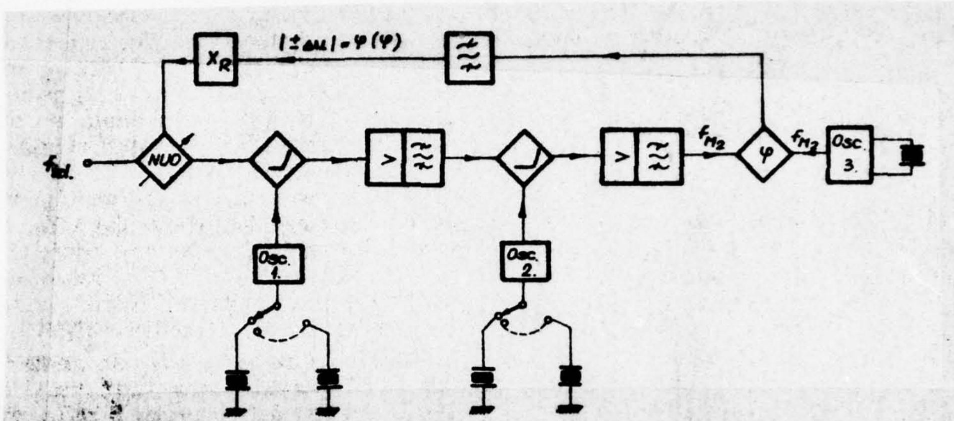
$$f_{out_1} = 0.1 + 17 + 7.9 + 0.1\ (10.0 + 0) = 25 \text{ MHz}$$

and on the last channel

$$f_{out_{100}} = 0.1 + 17 + 7.9 + 0.1\ (10.9 + 9) = 34.9 \text{ MHz}.$$

2. Analytical method of frequency synthesis with a regulation loop employing a phase discriminator.

The diagram for the analytical method of frequency synthesis with a regulation loop employing a phase discriminator (comparator) is shown in Scheme 24.



Scheme 24

Frequency analysis that produces the desired signal in an indirect way is often called indirect synthesis.

Fast frequency changes and very high frequency stability with a pure output signal are requirements that are nowadays demanded more and more in overcrowded frequency areas. Because of this, systems built on the principle of frequency analysis find their full use. Systems built on this principle generate a clear output signal, as the concomitant mixing products are suppressed by about 80-100 dB below the level of the desired frequency.

The phase discriminator (φ) compares the basic oscillator frequency with the frequency obtained by multiplication or division from the reference oscillator (OSC.3) - the reference frequency normal. The regulating voltage amplitude that is obtained as a result of the comparison in the phase discriminator depends on the input signal phase difference. This voltage acts on the reactance circuit X_R which leads the voltage governed oscillator (VGO) is the central frequency f_{M2}, the reference frequency normal.

The regulation of the VGO may be a) sinusoidal or b) by impulse.

a) Regulation of VGO frequency by a sinusoidal signal.

Let us prove that the phase discriminator output voltage which through the reactance circuit (varicap) regulates the frequency of the VGO depends on the cosine of the phase angle of the incoming signals.

If we bring to the phase discriminator (Scheme 25) two harmonic signals U_0 (phase 0), with frequency f_1, and U_φ (phase φ) with frequency f_2, then the diode voltage is

$$
\begin{aligned}
U_{D1} &= U_3 + U_1 \\
U_{D2} &= U_3 - U_2
\end{aligned}
\qquad (24)
$$

Let

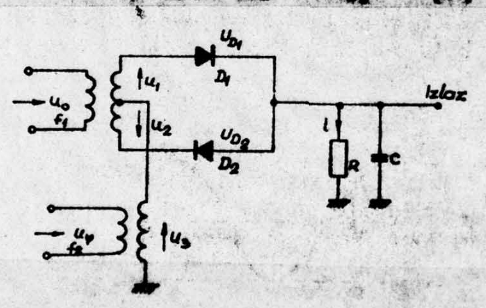
$$f_1 \neq f_2 \ \text{ i } \ \Delta f = f_1 - f_2 \qquad (25)$$

The current through resistor R is

$$i = i_{D1} - i_{D2} \qquad (26)$$

The currents through diodes D_1 and D_2 can be written as

$$
\begin{aligned}
i_{D1} &= I_0 + \alpha U_{D1} + \beta U_{D1}^2 \\
i_{D2} &= I_0 + \alpha U_{D2} + \beta M^2_{D2}
\end{aligned}
\qquad (27)
$$



Scheme 25

Momentary voltage values on the secondary transformers can be shown as

$$
\begin{aligned}
u_1 &= U_1 \sin \omega t = U \sin \omega t \\
u_2 &= U_2 \sin \omega t = U \sin \omega t \\
u_3 &= U_3 \sin (\omega t + \varphi) = U \sin (W t + \varphi)
\end{aligned}
\qquad (28)
$$

if $U_1 = U_2 = U_3 = U$.

In view of eqatuions 24, 27, and 28, equation 26 becomes

$$\begin{aligned} i = I_0 + \alpha\,[U \sin(\omega t+\varphi) + U \sin \omega t] + \\ +\beta\,[U \sin(\omega t+\varphi) + U \sin \omega t]^2 - \\ -\{I_0 + \alpha\,[U \sin(\omega t+\varphi) - U \sin \omega t] + \\ +\beta\,[U \sin(\omega t+\varphi) + U \sin \omega t]^2\} = \\ = 2\beta U^2 \cos\varphi + 2\alpha U \sin \omega t - \\ -2\beta U^2 \cos(2\omega t+\varphi) \qquad (29) \end{aligned}$$

The second and third term in the previous equation shorts itself on the mass through the condenser C, whereas the first term creates an output voltage on the resistor R.

The phase discriminator output voltage is

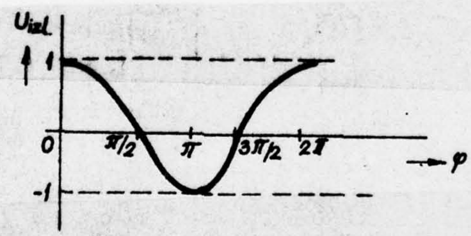
$$U_{izl.} = 2R\beta U^2 \cos\varphi \qquad (30)$$

Or, if we denote the amplitude $2R\beta U^2$ as voltage U', the output voltage is

$$U_{izl.} = U' \cos\varphi \qquad (31)$$

It is seen from equation 31 that the output voltage phase of the phase discriminatior, which through the reactance circuit regulates the VGO, is directly proportional to the cosine of the input signal phase angle.

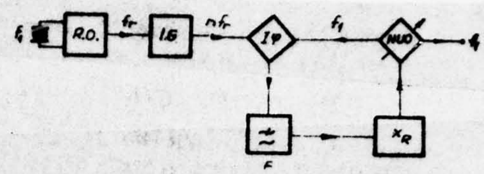
The dependence of the output voltage on the phase angle of the incoming signals is shown in Scheme 26.



Scheme 26

b) Impulse frequency regulation of a VGO.

The diagram of a system for impulse frequency regulation of VGO is shown in Scheme 27.



Scheme 27

The frequency of the VGO is controlled through the loop by impulse harmonics with the speed of repetition of the chosen reference frequency. If the reference frequency stability is high, the governed oscillator has a high frequency stability as well.

The reference frequency signal which is generated in the reference oscillator (R.O.) is transformed in the impulse generator (I.G.) into a series of short impulses with repetition frequency f_r.

The VGO is synchronized and tuned with frequency f_1 or with the n-th multiple of f_r. With coarse tuning the VGO is set to the frequency of n-th harmonic with precision $\pm$ 0.5 f_r. The penetration of undesired harmonics into the reactance circuit X_R is prevented by the low-pass filter F.

The reactance circuit X_R is used for fine tuning of the VGO frequency.

A voltage appears at the output of the impulse phase discriminator (I.φ.). Let the frequency of this signal equal to the difference between f_1 and nf_r, ie.,

$$\Delta f = f_1 - nf_r \qquad (32)$$

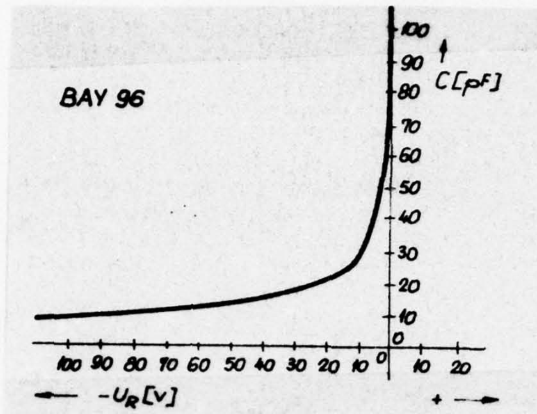
If (Δf) is lower than the limiting filter F frequency then this signal is brought to the reactance link X_R.

The reactance link is most often a capacitance diode (varactor) with inverse polarization.

The capacitance characteristic of the varactor BAY 96 with f = 1 MHz is shown in Scheme 28.

The capacitance of the capacitance diode with a given voltage U_R is calculated by the formula

$$C = C_{min}\left(\frac{U_D - U_Z}{U_D - U}\right) \cdot \gamma \qquad (33)$$



Scheme 28

where C_{min} is the capacitance at cutin voltage; U_D - the diffusion voltage (with silicon diodes 0.5 ... 0.7 V, with germanium $\approx$0.3 V); U_Z - cutin voltage (Zener voltage); γ- number between 0.33 and 0.5, depending on the technology of the diode; C - capacitance at voltage U.

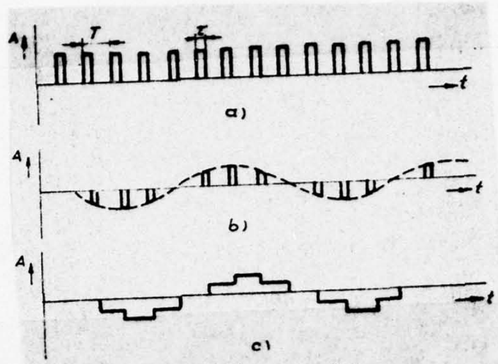
Regulating voltage $+\Delta U$ at the output of Iφ causes $-\Delta C$ in the varactor, and an increase of the VGO frequency toward the specified harmonic of the reference frequency. An output voltage of $-\Delta U$ at the circuit Iφ causes a lowering of the VGO frequency via the varactor.

By increasing Δf at the output of the phase discriminator, the process is speeded up, and by decreasing Δf the process is slowed down.

When the frequency of the variable oscillator (VGO) and the reference frequency harmonic are equal at the input of the impulse phase discriminator, then impulses of constant amplitude are produced as the output of the circuit (Scheme 29a).

If the frequencies are not the same, then the impulse phase discriminator output voltage changes as the cosine with frequency $f = f_1 - nf_r$ (Scheme 29 b).

The condenser C at the impulse phase discriminator output serves as a memory element. From the moment of impulse termination to the moment of the arrival of the next impulse it retains the momentary voltage value (Scheme 29c).



Scheme 29

It is essential that the time constant for condenser loading is considerably smaller than the impulse duration τ, and that the time constant for condenser discharge is considerably larger than the impulse period T.

This is guaranteed by the internal resistance of I9 which is low during the pulse, and high during the pause.

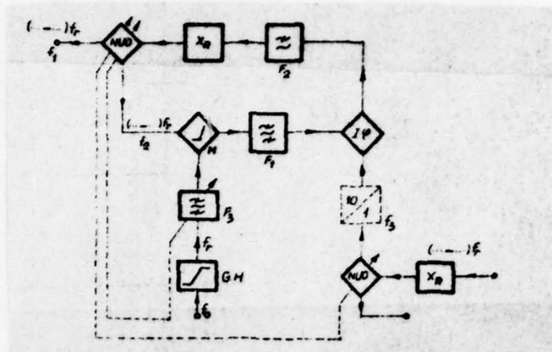
With the development of the electron tube model E-80T which acts as a phase discriminator, the problem of creating sufficiently short pulses is solved in case of sufficiently large VGO frequency. In the tube the sinusoidal voltage is used to control the electron beam path. The electronic stream moves sinusoidally back and forth over the tube screen with very narrow slits. The moment the electronic beam passes the slit, the anode creates a short lived current pulse. During the negative half-period the beam is damped with a correspoding screen grid potential. The sinusoidal VGO voltage is led to the other regulating tube screen grid. The anode current impulse depends on the phase difference of the two signals and amounts to a few microamperes.

The maximum VGO distuning that can be compensated by the reactance circuit is defined as the holding region, or in other words, the maximal region within which the variable oscillator frequency can be changed by the reactance circuit is called the holding range.

The frequency region within which the VGO is automatically synchronized is called the locking range.

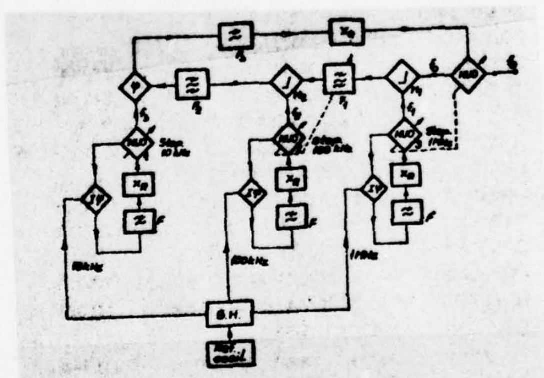
If the cutoff filter frequency is smaller than the cutoff loop frequency, the locking range is smaller than the holding range due to filter F damping.

The principle for producing synthesizer decades with an IGO and with an addition loop is shown in Scheme 30.



Scheme 30

The method for producing decades with two mixers is shown in Scheme 31.



Scheme 31

Frequencies f_1, f_2, and f_3 are obtained in IGO loops from oscillator decade outputs ($VGO_{1...3}$) using impulse phase discriminators.

Signal fed into mixers and the phase discriminator (φ) are sinusoidal in character.

To prevent synchronization with another frequency the output oscillator of the second decade and the band-pass filter F_1 are tuned simultaneously.

The comparison signal from the phase discriminator is led through filter F_3 and the reactance circuit to tune the the frequency of the main oscillator to f.

3. Construction of multiple channel oscillators by the analytical method of frequency synthesis with a regulation loop employing a phase discriminator.

Due to the many mixings, multiplications and divisions of frequencies that are often encountered in the construction of synthesizers, such a signal can not be used in transmitters as it contains harmonics that can not be eliminated.

This problem can be solved by a specific construction of the synthesizer as shown in Scheme 32.

Within the frequency range from 2.5 to 12499 MHz the synthesizer generates 10000 channels in jumps of 1 kHz.

Five output oscillators that cover the entire frequency range of the synthesizer are connected to the synthesizer output.

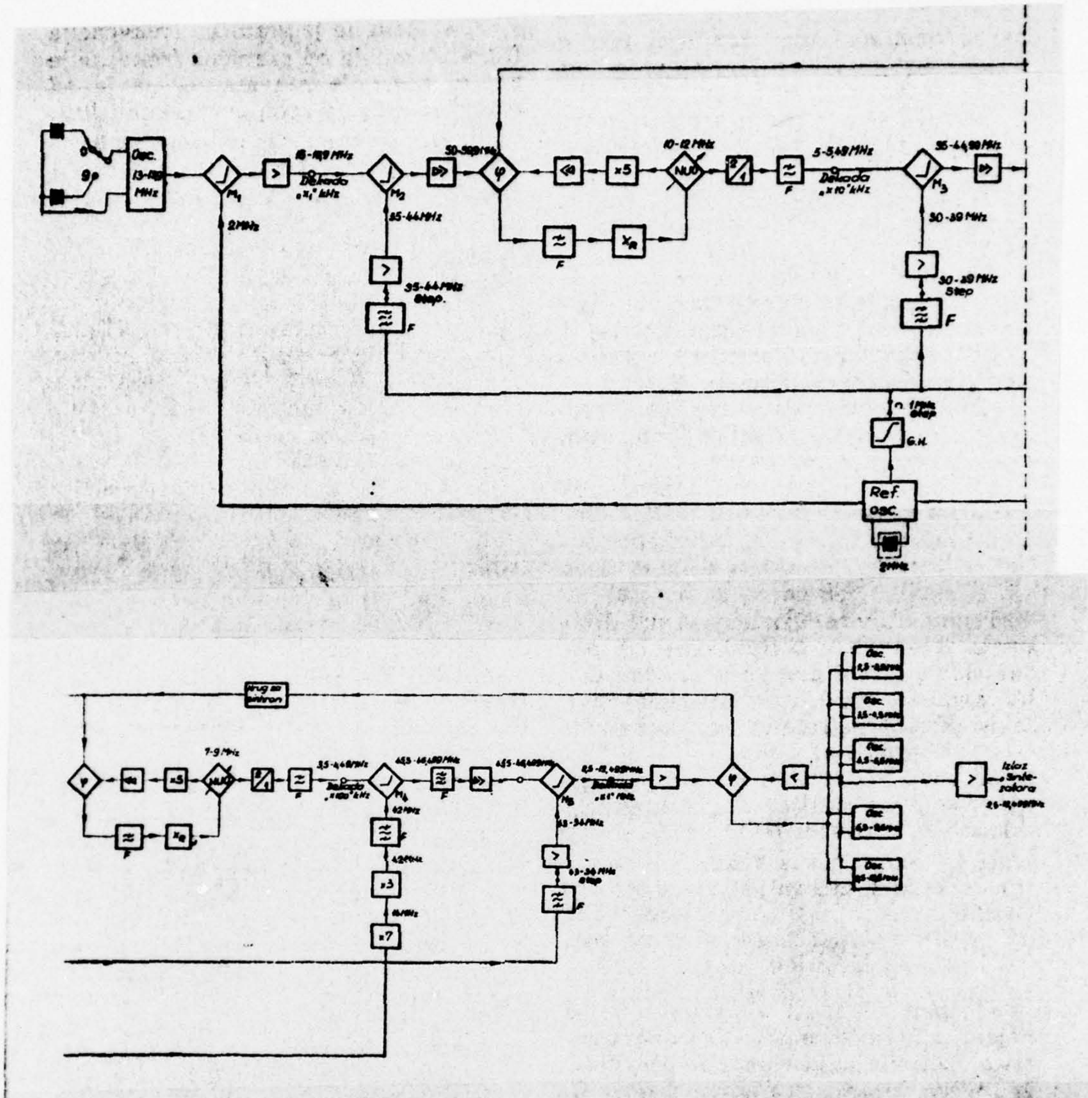
The functional ranges of the oscillators are 2.5 - 3.5 MHz, 3.5 - 4.5 MHz, 4.5 - 6.5 MHz, 6.5 - 9.5 MHz, and 9.5 - 12.5 MHz.

When selecting the synthesizer frequency "Xl" MHz at the decade output, the output oscillator, the functional range of which contains the selected frequency, is automatically switched on.

The phase comparator compares the output oscillator signal with the synthesizer reference signal of given precision and stability.

In other words, the transmitted synthesizer output signal is the signal from one of the five output oscillators, whereas the entire synthesizer serves as a generator of the reference signal of needed precision and stability.

The result of the signal comparison in the phase comparator is an either positive or negative direct voltage that appears at the phase comparator output. The magnitude and polarity of the voltage depends on the relative phase of the compared signals. This voltage acts reversibly on the varicap



Scheme 32

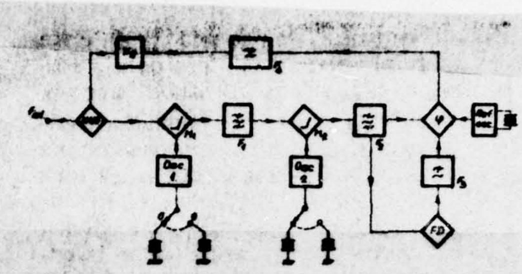
diode in the oscillator loop of the chosen output oscillator and diminishes the phase difference. In this way the sinusoidal oscillator voltage receives the stability and precision of the reference signal.

A synchronizing loop connects the phase comparator at the synthesizer output with the phase comparators of the second and third decade. The synchronizing loop oscillator signal of a given level and frequency helps equalize the frequencies from the second mixer M_2 and the fifth harmonic of

the 10-12 MHz oscillator and from the third mixer M_3 and the fifth harmonic of th 7-9 MHz oscillator in the synthesizer phase comparators.

4. Analytical method of frequency synthesis with a regulation loop employing a frequency and a phase discriminator.

The diagram for this method is shown in Scheme 33.



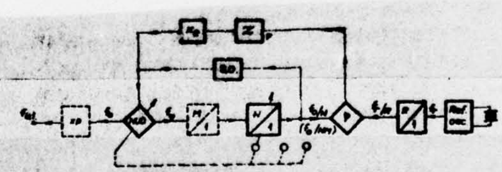
Scheme 33

The frequency discriminator that is connected in series with the phase comparator helps in establishing the desired frequency forming the additional regulating loop.

IV. DIGITAL FREQUENCY SYNTHESIZERS

If the regulation loop of the VGO contains a variable divider by N (electronic counter) then such a system is called a digital frequency synthesizer.

The diagram of a digital frequency synthesizer is shown in Scheme 34.



Scheme 34

With a variable frequency division coefficient and simultaneous tuning of the VGO the system can produce a stable frequency that depends exclusively on the features of the reference oscilloscope.

Comparing signals f_o/N and f_r/R a correction signal, led from the phase discriminator through the filter F and the reactance circuit X_R, sets the voltage regulated oscillator on f_o.

At the moment of oscillator synchronization the following relationship holds

$$\frac{f_o}{N} = \frac{f_r}{R} \tag{34}$$

The additional synchronization loop that contains the synchronizing oscillator (S.O.) governs the frequency of the VGO for coarse frequency selection around f_o. The moment the digital divider signal appears at the phase discriminator input, the synchronization circuit is connected, and the phase discriminator takes over the regulation of the frequency oscillator through F and X_R.

Chosing a low cutoff frequency for filter F in the regulation loop accomplishes

--- a lowering of spurious noise (impulse disturbances, humming) and

--- a lowering of undesired output signal modulation evoked by the variable reactance element (varicap) supply voltage.

However, the dynamic process of oscillator synchronization and the transition during channel change or while restoring disturbed synchronization require a wide filter pass-range. Therefore, filter F must have a small time constant due to the fast system reaction.

It follows that filter F has to satisfy two opposing requirements: lowering of disturbances and a fast response.

In practice this problem is solved by compromise. Often in the digital divider system the VGO output frequency is greater than the digital divider cutoff frequency and is generally around 15-25 MHz. For this reason a fixed-M divider is inserted before the digital divider to lower the VGO frequency into the digital divider working range. In that case the frequency of the digital divider output signal is f_o/NM which together with the signal f_r/R is brought into the phase comparator for comparison.

The relationship $f_o/MN = f_r/R$ is satisfied at the moment of VGO synchronization.

If the variable oscillator frequency f_o is so large that it is not easy or economical to divide it by M in the corresponding fixed divider which is inserted in front of the digital divider, then such a signal is not used as the synthesizer output signal.

In such a case a multiplier with a factor of P is connected at the synthesizer output. The synthesizer output signal frequency is then

$$f_{out} = P \cdot f_o \qquad (35)$$

If a fine graduation of frequency steps is desired, the digital divider division coefficient N is very large.

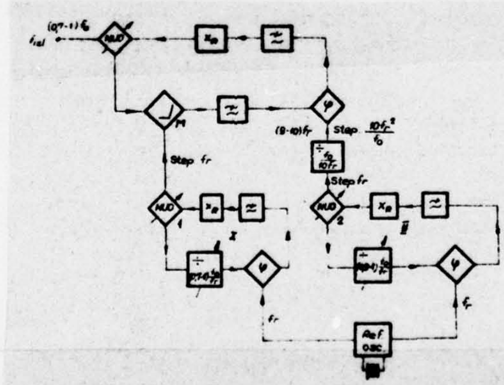
For example, with a variable oscillator with f_o = 30 MHz and f_r = 100 Hz, for a 100-Hz step an N = 300000 is needed.

Digital variable frequency dividers are limited also with respect to the minimal step.

If, for example, a synthesizer with a spectrum of up to 30 MHz and with 100-Hz steps is needed then a digital variable divider could not accomplish this task. For this reason, addition loops are used here as well.

Scheme 35 shows the diagram of a synthesizer with two counterloops, one fixed divider, and an addition loop.

Such an arrangement is used in the Philips RY 746 synthesizer.



Scheme 35

After the division, the frequency steps in loop I must be covered by loop II such that the frequency range in the addition loop phase comparator is f_r. The VGO_1 frequency interval is $(0.7\text{-}1)f_o$ and the VGO_2 $(0.9\text{-}1)f_o$. At the variable oscillator output the VGO frequency changes in steps of f_r, but at the VGO output the step is even smaller due to the division by $f_o/10f_r$, such that spectrum $(9\text{-}10)f_r$ in steps of $10f_r^2/f_o$ is brought to the frequency discriminator.

If the output variable-oscillator frequency is f_o = 100 MHz and the reference oscillator frequency f_r = 10 kHz, then the minimal steps are 10 Hz.

Programmed dividers (electronic counters) are complex circuits that have to meet the following requirements

--- high functional speed

--- simple setting of desired division ratio

--- simple extension of division number ratio

The faster the functional divider speed the larger is the maximal frequency that it can divide.

Thus the functional VGO frequency range can be enlarged without the introduction of another fixed divider between the oscillator and the programmed divider.

In constructing a programmed divider using the decade system with a synthesizer front-plate functional frequency read-out, the programming switches are connected with switches for 1 MHz, 100 kHz, 10 kHz, and 1 kHz selection.

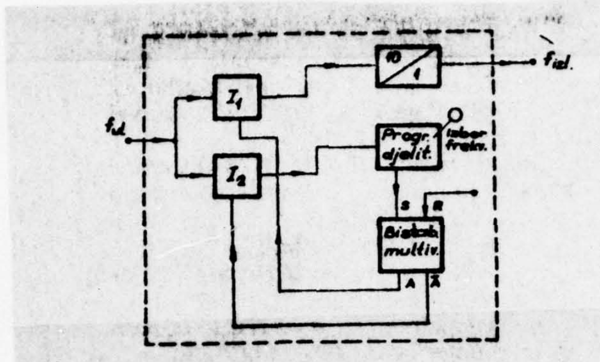
Usually decades are independently programmed units constructed with logic loops.

Such circuits are quite complex and can be constructed using integral loops. The advantage of such circuits is in the fact that they do not contain any filters.

At the present technological level of programmable dividers with high frequencies, these circuits use considerable amount of energy.

The decade logic loops are shown in Scheme 36.

When the impulse arrives at the decade input, the bistable multivibrator (A) output voltage magnitude is "0" which causes the engagement of the coincidental loop I_1. In this case, the bistable multivibrator output signal appears as "1" which opens the coincidental loop I_2.



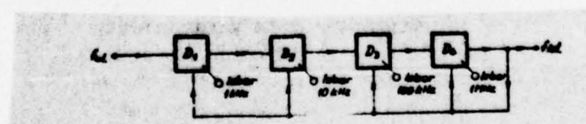
Scheme 36

The programmed divider counts the chosen number of impulses over n_i between 0 and 9. When the given number of impulses is counted, output S influences a change in the bistable multivibrator state, which with its output states opens the coincidental circuit I_1 and closes I_2.

A string of input impulses is led through the coincidental loop I_1 to the fixed 10-divider. The first impulse appears as the output of this divider after $10 + n_i$ input impulses, the second after $2 \cdot 10 + n_i = 20 + n_i$, the third after $30 + n_i$ etc. These impulses represent input pulses for the next decade.

The impulse of the last decades, formed by a programmed countercycle of the whole circuit, is used also for the automatic cycle repetition through the bistable multivibrator input R.

The diagram for a programmed divider with four decades D_1 - D_4 is shown in Scheme 37.



Scheme 37

Let us say that division with n = 7456 is needed. Decade D_4 is programmed for division with 7, D_3 with 4, D_2 with 5, and D_1 with 6.

After 7 impulses at the decade D_3 output, the first impulse appears at the decade D_4 output. At the decade D_3 output, the first impulse appears after 4 + 10 = 14, the second after $2 \cdot 10 + 4 = 24$, the third after $3 \cdot 10 + 4 = 34$, the fourth after $4 \cdot 10 + 4 = 44$, and the seventh after 74 impulses at the decade D_2 output. Therefore after 74 impulses at the decade D_2 output, an impulse appears at the decade D_4 output. That is, D_4 and D_3 together divide with the ratio 74.

At the decade D_2 output the first impulse appears after 10 + 5 = 15, the second after 25, and the 74th after $74 \cdot 10 + 5 = 745$ impulses at the first decade D_1 output.

At the decade D_1 output the first impulse appears after 10 + 6 impulses, the second after $2 \cdot 10 + 6 = 26$, and the 745th after $745 \cdot 10 + 6 = 7456$ impulses at the first decade input.

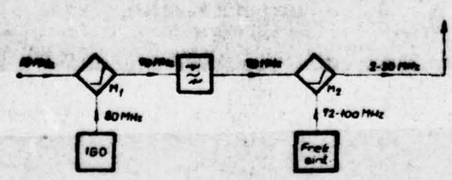
Therefore, the first impulse appears at the output after 7456 impulses at the input which are simultaneously led into programmed dividers.

The last decade D_4 contains only the divider with a variable division ratio and does not contain the coincidental circuit I_1 or the fixed divider.

The impulse appears at its output, therefore, after the completion of the desired programmed counting cycle of the entire circuit. This impulse is simultaneously used to repeat (at the bistable multivibrator input R) the cycle of the entire circuit automatically.

V. APPLICATION OF ELECTRONICALLY TUNED SYNTHESIZERS IN HF RADIO-RECEIVERS AND IN TRANSMITTER CIRCUITS.

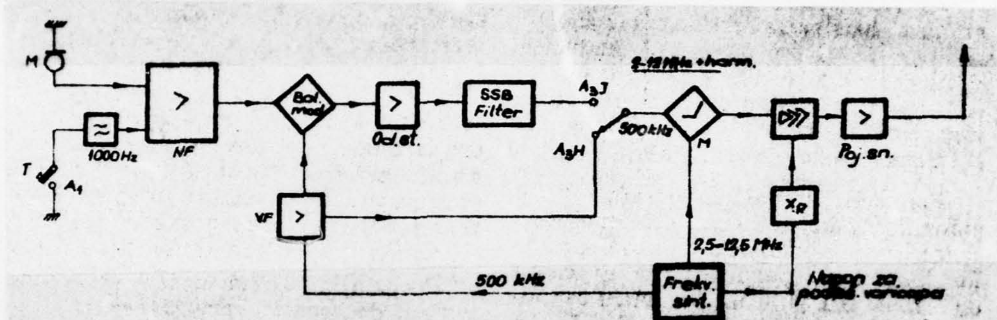
The diagram for the application of a frequency synthesizer in the impulse part of a HF radio transmitter circuit is shown in Scheme 38.



Scheme 38

A modulated 10-MHz signal and a 80-MHz signal, generated, for example, in a IGO loop is brought to the first mixer M_1 which functions on the basis of frequency difference. The 70-MHz frequency-difference signal is selectively separated and led through the band pass filter F into the second mixer M_2. The difference between the 70 MHz signal and the 72-100 MHz band of frequencies generated in the frequency synthesizer gives a HF radio transmitter spectrum of 2 to 30 MHz.

The diagram for the application of a frequency synthesizer in a SSB HF radio transmitter circuit is shown in Scheme 39.



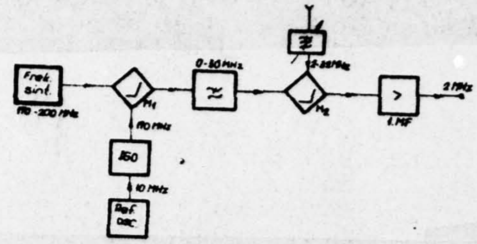
Scheme 39

The transmitter in the picture has several functions: A_1, A_3J, and A_3H. The synthesizer generates signals from 500 kHz and a spectrum of frequencies from 2.5 to 12.5 MHz which allow for the many transmitter functions. The synthesizer also creates a voltage for tuning the HF selective amplifiers through X_R (varicap).

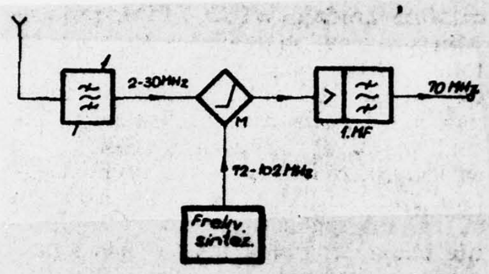
Schemes 40 and 41 illustrate the method for the application of electronically tuned synthesizers within a HF radio receiver circuit.

The first diagram illustrates the use of a frequency synthesizer in a HF radio receiver circuit for obtaining low intermediate frequencies.

Scheme 41 illustrates the application of a frequency synthesizer in a HF radio receiver circuit for obtaining high intermediate frequencies.



Scheme 40



Scheme 41

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